Images of possible fossil collision structures beneath the Eastern Ghats belt, India, from P and S receiver functions

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ABSTRACT

The Proterozoic Eastern Ghats belt of India is often believed to be the ancient analogue of the present-day Himalayas. However, geological and geophysical signatures that can be traced and linked to the Eastern Ghats belt orogen due to a Precambrian collisional episode are sparse and evidence of such a geotectonic process in the deep lithosphere remains elusive. Utilizing the P and S receiver function imaging technique, we present depth signatures of this convergence event and its lateral extent. Approximately 2000 P and S receiver functions that predominantly sample the Eastern Dharwar craton–Eastern Ghats belt reveal the presence of two distinct westerly dipping interfaces at depths centered on 150 km and 200 km in the study region. Drawing analogy from similar tectonic settings of Proterozoic age and younger that affected this region, we interpret these boundaries to represent remanent structures fashioned by the collisional processes that affected this region. Recent geological, geochemical, and geochronological evidence from the region strongly favors interpretation of our delineated dipping structures as possible vestiges of a Proterozoic collision event that are preserved due to their coherent translation with the overlying lithosphere. Due to this long-lasting record of Proterozoic tectonics, our results add a complication to simple models of the Indian subcontinent in which relatively thin lithosphere underwent rapid transit during the Cretaceous.

INTRODUCTION

The Eastern Ghats belt, juxtaposed with the Eastern Dharwar craton of the Precambrian South Indian Shield (Fig. 1A), has a rich milieu of varied rock types and petrotectonic settings and is viewed as a characteristic Precambrian collisional orogen based on intense detailed structural, mineralogical, petrological, and geochemical studies coupled with geochemical analyses on the rock and mineral assemblages (Leelanandam et al., 2006; Vijaya Kumar and Leelanandam, 2008; Mukhopadhyay and Basak, 2009). However, seismological information on the deep structure of the Eastern Dharwar craton in general, and particularly beneath the Eastern Ghats belt, remains sparse. Gravity signatures in this region reveal that the entire length of the Eastern Ghats belt is characterized by a steep positive-gradient gravity anomaly ranging from ~50 to +30 mGal, whereas the adjoining cratonic region shows a more uniform pattern of low anomalies (~−60 mGal) with smooth variations. Such paired-gravity anomalies accompanied by high gradients, as observed along the cratonic and Eastern Ghats belt contact regions, often characterize suture zones (Gibb and Thomas, 1976; Kaila and Bhattacharya, 1981). However, the depth disposition and lateral extent of this collision signature still remain elusive.

Utilizing P-to-S (Ps) and recently developed S-to-P (Sp) receiver functions (Vinnik, 1977; Farra and Vinnik, 2000), we attempt to focus on the mantle stratigraphy beneath the Eastern Ghats belt–Eastern Dharwar craton and interpret their significance in the aforementioned tectonic context. The seismic station-event locations (Figs. 1A and 1B), with reference to our study area, are positioned in a manner where the P and S receiver function pierce points (Fig. 1A) sample the mantle beneath the Eastern Ghats belt and the adjoining craton representatively. The P and S receiver functions, with their attendant limitations and advantages, can both supplement and complement each other in terms of their resolution, frequency content, sensitivity to transitions in physical properties, and unambiguous identification of conversions from seismic interfaces in the shallow mantle (e.g., Farra and Vinnik, 2000). With this understanding, we analyze data from four available permanent broadband stations (Fig. 1A) to image the deep lithosphere beneath the Eastern Ghats belt–Eastern Dharwar craton. Finally, we present our results in both regional and global context and discuss their geodynamic implications.

DATA AND APPROACHES

Four seismological stations (Fig. 1A) operated by the National Geophysical Research Institute, India, HYB, KDM, CUD, and DHD, yield ~1500 P and 900 S receiver functions, mostly for the period 2001–2005. Clear records of P and S waves from earthquakes with magnitudes larger than 5.5 and having a relatively high signal-to-noise ratio (SNR ≥ 3) were selected to construct the P and S receiver functions. The range of band-pass periods best suited for both P and S receiver function data varied from a minimum of 1.5 or 3 s up to a maximum of 10 or 12 s. We followed the methods described by Vinnik (1977) to construct and treat the P receiver functions. While calculating the S receiver functions, we used a technique introduced by Bianchi (2008), though it is in essence similar to that proposed by Farra and Vinnik (2000). We first rotated the original vertical (Z), north-south (N), and east-west (E) recordings to vertical (Z), radial (R), and transverse (T) components using back-azimuth information. Subsequently, the Z and R components were further rotated into local ray coordinate system L- (P energy) and Q- (SV energy) components, respectively, involving the angle of incidence for better isolation of the P and SV energy from the incident wavefield. This was followed by deconvolution of the Q-component from the L-component to obtain S receiver functions. To arrive at the optimal/correct angle of incidence to obtain proper coordinate transformation from ZRT to LQT, we used polarization results from three different...
functions prior to their summation. Such move-
slowness (6.4 s per degree), to individual receiver
functions. ZNE recordings and thereby to construct the S
receiver functions. The respective receiver functions were binned
exclusively the Archean cratonic block, and (2) those sampling the Proterozoic Eastern Ghats belt. This clear separation was done using the suture demarcated from gravity observations (Fig. 1A; Kaila and Bhatia, 1981) as a guide. The respective receiver functions were binned by their pierce-point locations. This treatment of the data is significant because of our objective to map the deeper lithosphere in the study area. This facilitates the discussion of our findings in the geotectonic context related to the evolution of the Eastern Ghats belt.

RESULTS AND DISCUSSION

In our final analysis, ~2200 Ps and Sp receiver functions were used. The Ps and Pps move-out–corrected sum traces and the Ps move-out–corrected distance stack sections for stations HYB (240 events) and KDM (442 events), shown as examples in Figures 2A and 2C, favor the positive polarity arrival at ~20 s as a Ps conversion. We hereafter refer to this phase as the Dc20s phase. The move-out–corrected Sp data (both sum trace and sections) at stations HYB (462 Sp data) and CUD (250 Sp data) presented in Figures 2B and 2D show two distinct arrivals.
Figure 2. Examples of P and S receiver function data. (A) Ps move-out–corrected P-receiver-function distance stack section at station HYB. In the top box, the multiple (Pps-phase) move-out–corrected sum trace (labeled 1) is followed by the Ps-phase move-out–corrected sum trace (labeled 2). The Moho (M) and Dc20s phases are marked in the sum traces. The Dc20s phase is clearly in addition to the Pps and Pss arrivals that are close by. (B) The distance move-out–corrected S-receiver-function stacks for station HYB reveal two distinct phases, Dc15s phase and Dc20s phase, which arrive in the delay time window 15–20 s and are separated by ~3 s. These new phases are observed consistently over a wide distance range used in our study. The Dc15s phase is perhaps masked by Pps (multiple) arrivals in (A), since their arrival times are very similar. On the contrary, note that there is no such interference by multiples in the S receiver functions. Sp conversion arising from the Moho boundary (M) and a low velocity layer (LVZ) are also indicated. (C) Same as A, for station KDM located to the east of HYB. (D) Same as B, for station CUD located south of HYB. All the data are move-out corrected, corresponding to a reference distance of 67°.
in the delay time window 15–20 s, separated by ~3 s and mimicking each other in their attitude. We name the earlier of these two phases as the \(Dc15s\) phase and the latter, as already mentioned, as the \(Dc20s\) phase. The inclined attitude of these Sp phases is indeed surprising because a move-out correction to a reference distance of 67° was already performed. We conjecture that these twin phases are possibly associated with dipping structures. Such speculation receives support from the observed variation in delay time (Fig. 3) of the designated \(Dc20s\) phase with back azimuth (BAZ dependence), especially in the range 37°–120°, in Ps data at HYB. The Sp data therefore suggest the possible pervasive nature of the shallow-mantle boundaries associated with the \(Dc15s\) and \(Dc20s\) phases in the Eastern Ghats belt–Eastern Dharwar craton.

If this ~20 s arrival is a true Ps conversion, it corresponds to an interface placed in the general depth range of ~200 km, a depth that usually corresponds to the Lehmann discontinuity (L-interface) in literature (Lehmann, 1959). Given the tectonic complexities associated with the craton–mobile belt contact regions, we are uncertain about the nomenclature to be adopted for this phase.

Our Ps receiver function results related to the crust at stations HYB, KDM, and CUD are in excellent agreement with those presented in Sarkar et al. (2003, and references therein). Likewise, Sp receiver functions at stations HYB, CUD (Figs. 2B and 2D), KDM, and DHD reproduce the reported negative phase (LVZ) at ~10 s retrieved through a similar approach by Kumar et al. (2007). In addition, our study identifies the presence of the previously mentioned shallow-mantle boundaries. Since we are focusing on imaging the deeper lithosphere to understand the collision episode in the Eastern Ghats belt, we refrain from discussing further details of results from earlier studies using these stations that were largely restricted to the crust and the upper 100 km of the mantle in this region. Hence, we emphasize the stated speculated inclined nature of the \(Dc15s\) and \(Dc20s\) phases observed from individual station data.

It is important to examine whether the observed intra- and interstation/region delays associated with phases \(Dc15s\) and \(Dc20s\) arise primarily from dipping upper-mantle stratification or are a result of sampling regions of differing upper-mantle velocities such as the Proterozoic Eastern Ghats belt and the adjoining Archean craton. To address this issue, we take advantage of the postulated suture outlined earlier and rearrange Ps and Sp data based on Eastern Ghats belt–craton pierce-point sampling to construct longitudinally and latitudinally oriented stacks for both these subregions. The cratonic Ps and Sp pierce-point data number 513 and 229, respectively, whereas for the Eastern Ghats belt, these numbers are 659 and 269, respectively (Fig. 1A). The rest (~150 Ps and ~350 Sp data), which sample the oceanic lithosphere, are not considered here.

Using bin intervals of 0.1° for Ps data and 0.5° for Sp phases, we summed individual receiver functions. We retained stacks that result from summing five or more traces in the case of P receiver functions and seven or more for Sp data. The longitudinal/latitudinal stacks representing both the craton and Eastern Ghats belt are presented as traces with equal spacing in Figure 4. Importantly, the P-receiver-function sum traces of longitudinal stack sections (Figs. 4A and 4B) representing both subregions (craton and Eastern Ghats belt) clearly show the already well-recognized \(Dc20s\) phase, which can also be traced with reasonable correlation in the individual stacks as well, at ~20 s. The respective S-receiver-function longitudinal/latitudinal stack sections (Figs. 4C–4F) unambiguously reveal the presence of two distinct Sp conversions (\(Dc15s\) and \(Dc20s\)) that share analogous attitudes in both the subregions.

Closer examination of individual stacks from several sections reveals the following: (1) The \(Dc15s\) and \(Dc20s\) arrivals in the craton longitudinal Sp stack section (Fig. 4C) show a clear shift in their arrivals with longitude. Beyond 80°E, they arrive ~1.5 s earlier than those registered by western longitudes. (2) Observations similar to craton longitudinal stacks are reflected in the Eastern Ghats belt longitudinal stack sections (Fig. 4D) also; however, the inflexion longitude is beyond 82°E, compared to 80°E in the craton. (3) The craton latitudinal stack section (Fig. 4E) is characterized by earlier arrivals of both these phases in the north.

**Figure 3.** Move-out–corrected P-receiver-function back-azimuth (BAZ) stack section. A BAZ binning interval of 3° is used to obtain the stacks. In contrast to the uniform arrivals related to the Moho (M) phase, a clear swerve in the Ps arrivals of the 20 s phase as a function of BAZ can be seen. This BAZ dependence, considered a diagnostic for presence of dipping structures, is notably pronounced in the BAZ range 40°–120° due to more data from this range, as also evident from Figure 1A.
(beyond 19°N). (4) The abrupt shift observed in \( Dc15s \) and \( Dc20s \) arrivals, characteristic of all the Sp sections (Figs. 4C–4E), becomes progressive from south to north in the Eastern Ghats belt latitudinal stack section (Fig. 4F), where the northern latitude stacks (beyond 17°N) show earlier arrival times.

In the case of contrasting upper-mantle velocities beneath the subregions of our study area, consistent with their Archean and Proterozoic characters, the \( Dc15s \) and \( Dc20s \) phases should show corresponding changes in their arrivals resulting from differences in the upper-mantle velocities beneath each sub-region. However, such anticipated intraterrane systematic shifts in delay times are not observed in the longitudinal/latitudinal stack sections. Instead, they show prominent intraterrane time shifts (Figs. 4C–4F) that are similar in both orientations. This indicates that the source of the observed inflexion in delay times (by \( \sim 1.5 \) s) of the designated phases, which simultaneously affects both the subregions, has an origin other than simple terrain velocity differences.

An important observation distilled from points 1–4, in conjunction with Figures 4C–4F, is that the NE portion of the study area encompassing both craton and Eastern Ghats belt shows distinct early arrivals of the \( Dc15s \) and \( Dc20s \) phases that get progressively delayed by \( \sim 1.5 \) s toward the opposite SW quadrant. This observed difference (\( \sim 1.5 \) s) in arrival times on opposing sides of the study area (NE and SW), irrespective of whether values were measured under the craton or Eastern Ghats belt, can best be explained by invoking the presence of westerly dipping interfaces associated with these seismic phases. Such an inference seems even more appropriate in the context of documented

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**Figure 4.** Move-out-corrected P and S receiver functions summed separately by their pierce-point longitudes/latitudes for the cratonic and Eastern Ghats belt subregions. (A) Craton Ps data are summed in 0.1° pierce-point longitudinal bins. The W-E longitude section reveals the clear presence of a Moho Ps phase around 5 s and its corresponding multiples (Pps and Pss) that arrive in the time window 12–20 s. An additional arrival designated \( Dc20s \), evident in the sum trace, can be traced in the individual stacks as well. (B) Same as A for subregion Eastern Ghats belt. (C) Craton S receiver functions in 0.5° longitudinal intervals are summed based on their pierce-point locations at 200 km depth. The \( Dc15s \) and \( Dc20s \) arrivals recognized earlier at individual stations are clearly traced throughout the study region in this longitudinal stack section. These Sp conversions are delayed in the west and arrive earlier in the eastern part. (D) Same as C, for Eastern Ghats belt. (E) Same as C, for craton latitudinal intervals. (F) Same as E, for Eastern Ghats belt.
collision in the study region related to the Eastern Ghats belt orogen (Vijaya Kumar and Leelanandam, 2008), which is also manifested in gravity data (Kaila and Bhatia, 1981).

In view of this discussion, we combined Sp data from the craton and Eastern Ghats belt subregions to construct a composite longitudinal stack section (Fig. 5). This section clearly delineates interfaces corresponding to the two (Dc15s and Dc20s) phases with a westerly dip. This is the first report of the presence of such velocity discontinuities in the study region.

**Tectonic History of the Eastern Ghats Belt and Subduction Signatures**

There is unanimity among researchers that the Eastern Ghats belt orogeny is a culmination of at least three well-documented tectonothermal events: the oldest corresponds to the pre-Grenvillian orogeny (>1.5 Ga), another is synchronous with the Grenville orogeny (ca. 1.2–1.0 Ga), and the latest is associated with the Pan-African orogeny (ca. 0.5 Ga). Their spatial extent and relative intensities, however, remain unclear (Mukhopadhyay and Basak, 2009). Of these, the pre-Grenvillian event is conspicuous by its absence in the northern part of the Eastern Ghats belt, which is mainly our study area (Fig. 6A). However, all three events are well recorded in the southern segment of the Eastern Ghats belt, especially around Kondapalli locality (Vijaya Kumar and Leelanandam, 2008). Studies based on deformed fabric in the Nellore-Khammam schist belt (see Fig. 6A) indicate two cycles of divergent deformation suggestive of bivalent collision along the Eastern Ghats belt, of which the first cycle is explained by invoking westward subduction in the region around 1.6 Ga (Saha, 2004). Record of such westward subduction is apparently contrary to the prevailing major view of eastward subduction (e.g., Gupta et al., 2000; Bhadra et al., 2004), which probably occurred at a later time, as the dominant mechanism in the evolution of the Eastern Ghats belt. However, unambiguous recognition of sutures in Archean and Proterozoic terranes is a rarity and is often controversial (Burke et al., 2003; Leelanandam et al., 2006).

In Figure 6B, we show a three-dimensional (3-D) perspective of the depth disposition of the delineated westerly dipping interface from 160 to 200 km (see also Fig. 5). Such a feature in deeper domains across Eastern Ghats belt–craton, coupled with recorded presence of (1) nepheline syenites that represent deformed alkaline rocks and carbonatites (DARCs; Leelanandam et al., 2006), (2) a paired gravity anomaly (Kaila and Bhatia, 1981), and (3) outcrops of ophiolites in the study area, encourages us to interpret the observed feature as representing a subduction-related relict preserved at these depths. Significantly, therefore, the delineated westerly dipping interface (Fig. 6B) in the northern segment of the Eastern Ghats belt (our study area) also can be preferentially linked to the recorded pre-Grenvillian westward (first) convergence event that has been established, so far, only in the southern segment (Saha, 2004; Vijaya Kumar and Leelanandam, 2008).

With regard to the Grenvillian collision episode, this event is dominated by eastward subduction and is often discussed in the context of evolution of the Eastern Ghats belt (Gupta et al., 2000; Bhadra et al., 2004). In view of our delineated westerly dipping feature (Fig. 6B), it appears that the tectonothermal events that occurred as a result of this younger collision episode, though widespread, left no indelible signatures in the tectosphere of the studied region. Another possibility could be that because the bulk of the landmass drifted away from India during the breakup of Gondwanaland, the spatial extent of the remnant geophysical signatures related to this later episode is small in the Indian part and is not reflected in our images. In this context, it is important to mention the latest paleomagnetic work in Pallavaram-Vandallur region, south of our study area, by Mondal et al. (2009). Their data do not record the Grenville episode of the Eastern Ghats belt, which is often construed as the major tectonothermal event in the evolution of the Eastern Ghats. Instead, rocks in this region retain signatures of uplift cooling and charnockite metamorphism at ca. 2.4–2.1 Ga. Mondal et al.’s measurements of anisotropy of magnetic susceptibility (AMS) to evaluate the distribution of directions of sample magnetizations in charnockites differ by ~60° with respect to the reported Grenville poles. Thus, it is possible that the subsequent tectonothermal events may not always leave their imprints on the earlier records. These findings allow us to speculate that the Grenville and later events perhaps have impacted those locales more, after which they drifted away from the Indian landmass during the Mesozoic breakup of the Gondwanaland. Therefore, our argument that the delineated westerly dipping surface is a reflection of the pre-Grenvillian collision episode seems justified.

In a global context, geophysical detection of ancient sutures is largely limited to seismic-reflection data. For example, reflection events associated with steeply to gently dipping structures extending 60–75 km into the mantle.

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**Figure 5.** Composite S-receiver-function longitudinal stacks of the entire Eastern Dharwar craton (craton and Eastern Ghats belt data). Data in 0.5° longitudinal intervals are summed based on their pierce-point locations at 200 km depth. The Dc15s (broken line) and Dc20s (inclined solid line) arrivals also shown in Figures 2 and 4 are clearly traced throughout the study region. These Sp conversions are delayed in the west and arrive earlier in the eastern part of the study region, suggesting their association with westerly dipping structures/interfaces. Line at ~5 s shows the Moho (M) arrivals. The negative phase around 10 s is designated as LVZ. See text for more details.
imaged beneath the Baltic Shield (Abramovitz et al., 1997), the Canadian Superior Province (Calvert et al., 1995), and northwestern India (Vijaya Rao et al., 2000) are interpreted as sutures. Therefore, the inferred present-day gentle dip of ~4°–5° from the Eastern Ghats belt data (Fig. 5) should not come as a surprise, since it compares well with the shallow angle of present-day dip (~7°) inferred from one of the lines of the BABEL experiment in the northern terrane of the Proterozoic Baltic Shield at a depth of 75–80 km (Abramovitz et al., 1997). It is important to note that the delineated dips are not necessarily a reflection of the original subduction angle, although Precambrian subduction-accretion complexes are generally characterized by shallow-angle subduction (Cawood et al., 2006). Integrated analysis of controlled source seismic and receiver function data across the Archean-Proterozoic Cheyenne belt suture zone in the Rocky Mountains shows the presence of a north-dipping mantle slab to at least 100 km depth related to a ca. 1.8 Ga collision event, the imprints of which have been retained since then (Rumpfhuber and Keller, 2009). Similar results from the same region are also reported from Deep Probe refraction experiments earlier by Gorman et al. (2002). Reflection images from a relatively younger orogen, the Paleozoic, Ural Mountain belt (Knapp et al., 1996; Steer et al., 1998) show clear presence of possible relict structures in the deep mantle at multiple depths, with the deepest located at a depth of ~225 km. These dipping mantle depth horizons imaged beneath collisional belts, ranging from the Archean through the Proterozoic to the Paleozoic, are viewed as remnants or relics of subduction-related processes preserved in the mantle (e.g., Abramovitz et al., 1997; Calvert et al., 1995; Cawood et al., 2006; Cook et al., 1998; Gorman et al., 2002; Knapp et al., 1996; Smythe, 1982; Steer et al., 1998; Vijaya Rao et al., 2000; Warner et al., 1996). Therefore, the collisional tectonic environment of the Eastern Ghats belt, its Proterozoic age,
and the distinct presence of a dipping structure at mantle depths (~150–200 km) in its underlying lithosphere provide a compelling comparison with the regions, results, and interpretations mentioned earlier.

**Pre-Grenvillian Evolution Model of the Eastern Ghats Belt and Major Geodynamic Implications**

The west-dipping plane delineated from seismological results in the depth range 160–200 km in our study area is best explained by invoking a tectonic evolution model akin to that proposed for the southern part of our study area by Vijaya Kumar and Leelanandam (2008). We speculate that the pre-Grenville rifting took place in the Archean cratonic protoliths in our study region (Fig. 7A), followed by eastward subduction of oceanic lithosphere, giving rise to an intra-oceanic island arc (Fig. 7B). In the next stage, following the accretion of the island arc and polarity reversal, formation of a continental margin of Andean type took place (Fig. 7C). The last stage is the continent-continent collision, which formed collision-related S-type granite plutons (Vijaya Kumar and Leelanandam, 2008; Mukhopadhyay and Basak, 2009, and references therein) and led to creation of a westerly dipping suture (Fig. 7D). Our geophysical data shown in Figures 5 and 6 therefore seem to mimic the attitude of this pre-Grenvillian westerly dipping suture.

The bottom panel of Figure 7 depicts the present-day status of the Eastern Ghats belt–craton region in a schematic manner. In the case that our interpretation of the delineated westerly dipping slab as a relict reminiscent of a paleo-subduction process is valid, then preservation of such subduction-related scars, at least since the Mesoproterozoic, is significant. Survival of such relict structures in the lithosphere, even during the Gondwanaland breakup, directly suggests that the tectospheric keel (lithospheric roots) beneath the craton and Eastern Ghats belt by far extends beyond 200 km depth and translates coherently with the overlying lithosphere, preserving the delineated ancient orogenic structures. Our results are in consonance with the concerns raised against thin cratonic lithospheres, which seem irreconcilable with latest robust global tomographic shear velocity models and teleseismic residuals (Romanowicz, 2009). Our finding, therefore, argues for a thick lithosphere beneath the study region and directly contradicts any model that envisages a thin Indian lithosphere. Thus, any geodynamic consequence that follows from a thin lithosphere model, such as rapid Indian plate transit during the Cretaceous, appears untenable. Finally, our
results add to the growing body of evidence that supports the operation of present-day plate-tectonic processes during Precambrian times.

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